Effect of temperature on soil respiration in a Chinese fir forest

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Abstract: Soil samples collected from the surface soil (0−10 cm) in an 88-year-old Chinese fir (*Cunninghamia lanceolata*) forest in Nanping, Fujian, China were incubated for 90 days at the temperatures of 15°C, 25°C and 35°C in laboratory. The soil CO_2 evolution rates were measured at the incubation time of 2, 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80 and 90 days. The results showed that CO_2 evolution rates of soil samples varied significantly with incubation time and temperature during the incubation period. Mean CO_2 evolution rate and cumulative amount of CO_2 evolution from soil were highest at 35°C, followed by those at 25°C, and 15°C. Substantial differences in CO_2 evolution rate were found in Q_{10} values calculated for the 2nd and 90th day of incubation. The Q_{10} value for the average CO_2 evolution rate was 2.0 at the temperature range of 15–25°C, but it decreased to 1.2 at 25– 35°C. Soil CO_2 evolution rates decreased with the incubation time. The cumulative mineralized C at the end of incubation period (on the 90th day) was less than 10% of the initial C amounts prior to incubation.

Keywords: forest soil; Chinese fir; respiration; temperature

Introduction

Climate change is mainly driven by increasing concentrations of atmospheric CO_2 (IPCC 2007). Prediction of future CO_2 concentrations significantly depends on the effect of global warming on the release of CO_2 from decomposing soil organic matter (Jones et al. 2005) and on the possible duration of this effect. Soil organic matter contains approximately 1500 Pg of carbon, constituting the biggest carbon pool in the Earth's terrestrial ecosystem (Post et al. 1982; Yang et al. 2004). The flux of carbon dioxide from soils (soil respiration) is about 25% of the total annual flux of carbon to the atmosphere and is estimated to be more than 68 Pg C per year (Schlesinger et al. 2000). Rising atmospheric CO_2 concentration is expected to increase soil temperature, which may stimulate the flux of carbon dioxide from soils, causing a positive feedback effect (Kirschbaum 1995; Ise et al. 2006).

As early as the 1920s, Lundegardh (1927) noted that soil respiration was correlated with various factors, including the temperature, moisture and nutrient content of the soil. The importance of the temperature dependence of soil respiration has been further emphasized in recent years due to the global warming issue (Reichstein et al. 2000; Kirschbaum 2006; Schindlbacher et al. 2008). However, we still do not adequately understand that how climate change would affect the mineralization or the storage of organic carbon in soils (Giardina et al. 2000; Knorr et al. 2005). Although we believe that higher global temperatures will increase the rates of microbial decomposition in soils, very few data document the magnitude or the duration of this effect in different soils and specific ecosystems (Kirschbaum 2006).

Chinese fir (*Cunninghamia lanceolata*), an important native conifer, has been widely planted for more than 1 000 years. The planting area of Chinese fir has reached 6×10^6 ha and accounted for 24% of total planted forest area of China (Yu 1996). We hypothesize that warmer temperatures may stimulate soil organic C decomposition in Chinese fir plantations. The aim of this study was to determine the effects of temperature on the rate and cumulative amount of soil CO_2 evolution during a relatively long-term incubation from an 88-year-old Chinese fir forest in southern China.

Materials and methods

Site description and soil sampling

The study area was located at Ancaoxia Forest Farm (26°28′N, 117°57′E, 200 m above sea level) in Nanping, Fujian, China. It is one of the central growing areas of Chinese fir. This area has a

middle subtropical monsoon climate with a mean annual temperature of 19.3ºC and a relative humidity of 83%. The mean annual precipitation is 1 669 mm, mainly occurring from March to August. Mean annual potential evapotranspiration is 1 413 mm. The soil in this area is red earth derived from granite (Humic Planosols in FAO system) with an average depth of more than 1 m.

An 88-year-old Chinese fir forest, with an average stand density of 750 stems·ha^{-1}, was chosen for investigation in 2006. The forest was located on southwestern aspects and 30° slope. Mean tree height and diameter at breast height were 32.2 m and 32.8 cm, respectively. The representative species for undergrowth in this stand was dominated by *Maesa japonica*, *Ficus hirta*, *Woodwardia japonica*, and *Dicranopteris dichotoma*.

Three plots with each area of 20 m × 20 m in size were established within this site for soil sampling. In June 2006, six soil cores per plot were collected at the depth of 0–10 cm using an auger with inner diameter of 8 cm, and then formed into one soil sample. The soil samples collected were sieved through a 2-mm sieve to remove rocks and plant roots. The main properties of surface soil (0–10 cm) are described in Table 1.

Table 1. Main characteristics of soils (0–10 cm) used for incubation

Parameters	Mean ± S.E.
Bulk density (g·cm^{-3})	1.10±0.12
Soil pH in water	4.7±0.3
Total N (%)	0.20±0.03
C/N ratio	11.2±1.3
Available N (mg·kg^{-1})	56.8±7.2
Available P (mg·kg^{-1})	3.2±0.4

Soil sample incubation and respiration rate measurement

Soil samples (20 g oven-dry weight) were placed in 1-L glass jars and incubated for 90 days at 50% of water-holding capacity and three temperatures (15, 25, and 35°C). Each temperature treatment was triplicated. The moisture of the samples was adjusted every 2 days with deionized water.

CO_2 evolution rates of soils incubated at 15, 25 and 35°C were measured at the incubation time of 2, 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80 and 90 days using the alkali absorption method (Anderson 1982). The soil evolved CO_2 was collected into 20-mL traps of 0.5-M NaOH solution and titrated with 0.5-M HCl after adding 5 mL of 1.5-M $BaCl_2$. The glass jars were regularly aerated to allow replenishment of O_2.

Q_{10} values were calculated based on the soil respiration rates measured at 10°C intervals. A standard exponential rate equation was used over a defined temperature interval to calculate the respiration coefficient, Q_{10},

$$B = \frac{\ln(\frac{R_2}{R_1})}{(T_2 - T_1)} \quad \text{...and...} \quad Q_{10} = e^{(10 \times B)} \tag{1}$$

where, R_1 and R_2 are the respiration rates at temperatures T_1 and T_2, respectively, and B is the respiration rate constant.

Measurement of total carbon content

Total carbon contents of the soil samples were analyzed prior to incubation. The soil samples were dried at 60°C for 2 days, then were ground and analyzed with a Vario EL Ⅲ CHNOS Elemental Analyzer.

Statistical analyses

All measurements given are the means of three replicates (±S.E.) on the basis of an oven-dry weight. The results were statistically analyzed by ANOVA, and significant differences ($P < 0.05$) between incubation temperatures were tested by a t- or F-test.

Results

CO_2 evolution rate of soil

CO_2 evolution rates of the incubated soils varied with incubation temperature and time (Fig. 1). During the 90-day incubation period, daily CO_2 evolution rates for all soil samples were characterized by an initial faster and a subsequent slower rate. The soil CO_2 evolution rates at all temperature treatments were lower at the end of incubation period than at the initial period. The variation in soil CO_2 evolution rates during the whole incubation period was less at 15°C than at 25°C and 35°C.

At the beginning of incubation, the CO_2 evolution rate of soil at 35°C was significantly higher than those at 15°C and 25°C (Fig. 1). By day 15, the CO_2 evolution rates of soils incubated at 25°C and 35°C fell to approximately the CO_2 evolution rate at 15°C and remained relatively constant thereafter. The most notable change in CO_2 evolution rate was found at 35°C incubation, for which the soil CO_2 evolution rate at the 10th day decreased by more than 80%, compared to that at the 2nd day (Fig. 1).

At 25°C and 35°C, the maximum CO_2 evolution rate occurred in the first 2 days, while at 15°C the CO_2 evolution rate was the highest on day 5. The mean CO_2 evolution rate was highest at 35°C during the incubation period, followed by those at 25°C and 15°C (Fig. 2).

Table 2. Q_{10} values calculated for soils incubated on the 2nd day (RES$_{ini}$) and the 90th day (RES$_{end}$) and the average respiration rates during the whole incubation period (RES$_{avg}$)

Temperature range (ºC)	RES$_{ini}$	RES$_{end}$	RES$_{avg}$
25–15	7.5±1.1a	2.3±0.2a	2.0±0.2a
35–25	2.2±0.3b	0.8±0.1b	1.2±0.1b

Notes: Values are means ±S.E. of three replicates. Means followed by different letters on the same column indicate significant differences at $P<0.05$.

The CO_2 evolution rates from the soil samples increased more obviously with a temperature increase from 15°C to 25°C, compared to that with a temperature increase from 25°C to 35°C (Fig. 2). Such difference was also reflected in the calculated Q_{10} values ($P<0.05$) (Table 2). Additionally, substantial differences in CO_2 evolution rate were found in Q_{10} values calculated for the 2nd and 90th day of incubation (Table 2). The Q_{10} value for the

average CO_2 evolution rate was 2.0 at the temperature range of
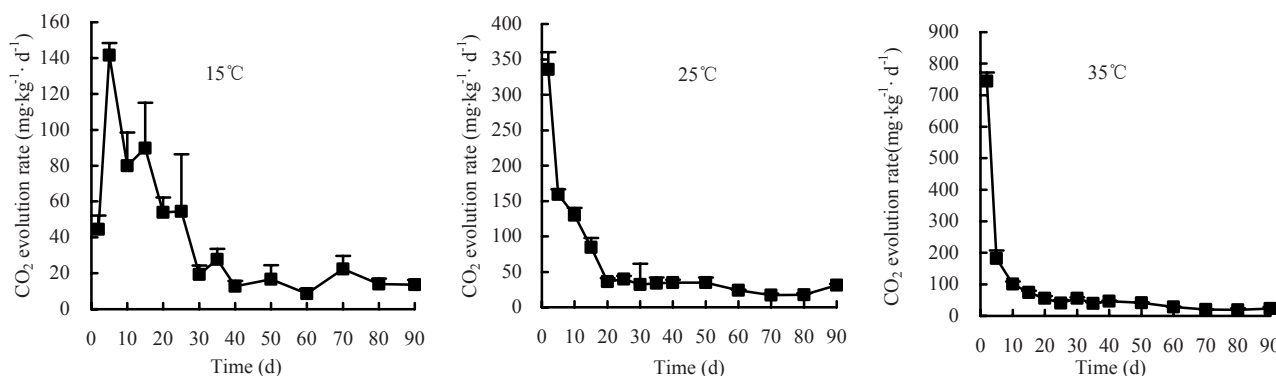
15–25°C, but it decreased to 1.2 at 25– 35°C.

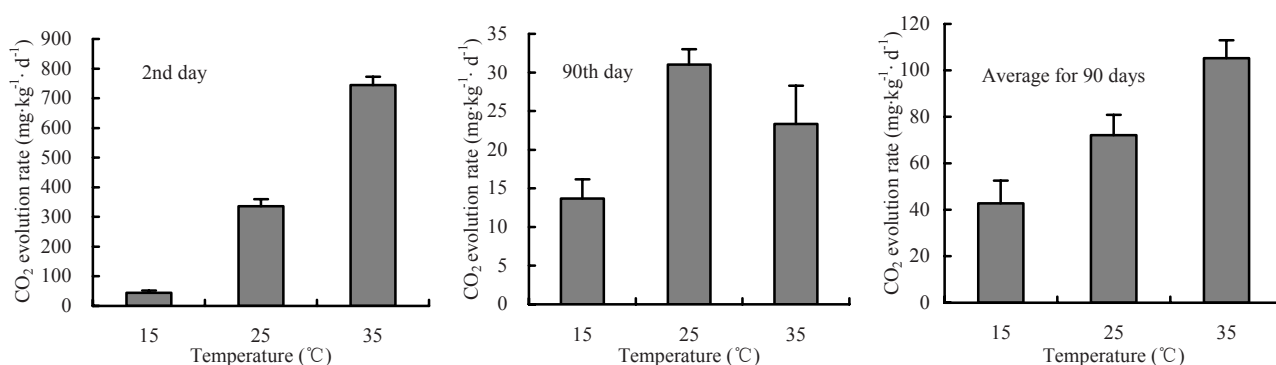**Fig. 1 Mean CO_2 evolution rate for surface soil (0−10 cm) at 15°C, 25°C and 35°C during the incubation period**

Fig. 2 Relationships between CO_2 evolution rate and temperature from soil samples

Cumulative soil CO_2 evolution

The amount of soil evolved CO_2 increased with increasing temperature from 15°C to 35°C; meanwhile, the cumulative mineralized C in all soil samples increased with the increase of incubation time, showing a subtle curvilinear tendency and no signs of levelling off even at the end of incubation period (Fig. 3).
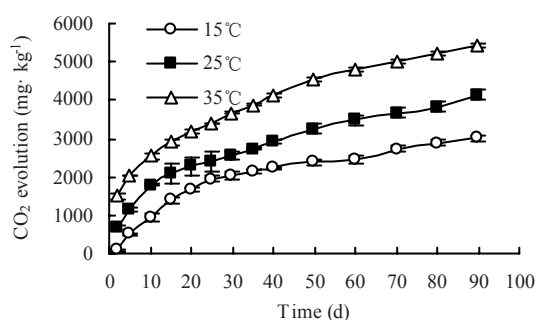

Fig. 3 Cumulative CO_2 evolution from surface soil (0−10 cm) at 15°C, 25°C and 35°C during the incubation period

There were significant differences ($P<0.05$) in cumulative mineralized C in soils incubated at different temperatures (Table 3). At 90th day of the incubation, the total amount of soil CO_2-C released was 822, 1130 and 1476 mg·kg^{-1} at 15°C, 25°C and

35°C, respectively.

Table 3. Cumulative mineralized C (C_m) at 15°C, 25°C and 35°C during the 90-day incubation period

Parameters	Incubation temperature		
	15°C	25°C	35°C
C_m (mg·kg^{-1})	822±24a	1130±31b	1476±43c
% Initial C mineralized	3.7±0.1a	5.1±0.2b	6.6±0.3c

Notes: Values are means±S.E. of three replicates. Means followed by different letters on the same row indicate significant differences at $P<0.05$.

The evolved C was also expressed as a percentage of the initial C (Table 3). For all soil samples, cumulative mineralized C at the end of incubation period was less than 10% of the initial C amounts prior to incubation, showing that a large proportion of the organic C remained unmineralized after 90 days of incubation. The higher incubation temperature may increase microbial activity and/or microbial biomass, resulting in the higher percentage of mineralized C in soil at 35°C (6.6% as against 3.7% and 5.1% at 15°C and 25°C respectively).

Discussion

CO_2 evolution

The result of soil CO_2 evolution rates in this study was agreed

with the findings of other soil-warming investigations (Leirós et al. 1999; Rustad et al. 2000; Fang et al. 2001). For example, Xu et al. (2006) found exponential increases in respiration rates with increasing temperature from measurements of temperate volcanic forest soils. Q_{10} value is the most important index of soil respiration, and is essential for accurate prediction of soil carbon response to global warming. The average Q_{10} values in our study fell within the range of Q_{10} calculated by previous investigators for soils incubated over a similar range of temperatures (Raich et al. 1992; Kirschbaum 1995), but were less than the Q_{10} values calculated by Xu et al. (2006). Our experiment results also showed that the temperature sensitivity of microbial respiration decreased with increasing temperature, which was in agreement with the result of Kirschbaum (1995).

The CO_2 evolution rates of incubated soils varied with the duration of incubation. Generally CO_2 evolution rate decreased with incubation time. Fast decrease in the CO_2 evolution rate with time indicated the presence of two different pools of organic matter: an easily degradable pool that was depleted early in the incubation, and a resistant, slowly degrading pool that remained after more available carbon sources had been used (Reichstein et al. 2005). The decrease in soil CO_2 evolution rate with time was similar to the results of Pohhacker and Zech (1995), suggesting that the amount of labile substrate was low relative to rates of respiration.

The fraction of total C respired throughout the incubation was calculated for each incubation temperature treatment using the initial C measurements and the respiration measurements. Results showed that the fraction of C respired increased with increasing incubation temperature (Table 3). The soils incubated at 35°C lost the most C relative to the total amount of C in the soil and about 7% of the total C was respired. The soils at 15°C evolved about 4% of their C content over the incubation time, while the soils at 25°C lost about 5% of their C content over 90 days. The flux of CO_2 from the soils was low relative to the total amounts of C in the soils, suggesting that a large fraction of soil organic matter was recalcitrant (Davidson et al. 2006; Silveira et al. 2008).

We acknowledged that this experiment was only in laboratory incubation condition, so the pool of labile C was not replenished by new inputs of organic C from roots and aboveground litterfall (unlike in the ecosystem). This factor might induce microbial starvation and associated modifications of microbial assimilation efficiency (Persson et al. 2000). Moreover, the pool of labile C was small, but was more rapidly degraded at higher temperatures, increasing the flux of CO_2 in soil respiration. The remaining soil organic matter was relatively resistant and its decomposition with temperature might be observed over long periods.

The effect of temperature on soil respiration

The temperature dependence of soil respiration is important because it determines that how strong the feedback from the expected warmer climate may be on the atmospheric CO_2 concentration. At present, a thorough discussion of the effects of temperature on microbial respiration is missing. Here we discussed

about soil respiration response to the temperature in incubated soil from an old-growth Chinese fir forest. The soil CO_2 evolution had rapid responses to increasing temperature in the studied soils, and this effect varied with different temperatures. In our experiments it was likely that microbial activity and microbial community structure would be different at 15, 25 and 35°C (Waldrop et al. 2004; Pietikainen et al. 2005; Sowerby et al. 2005; Zhang et al. 2005; Zyakun et al. 2005). Moreover, Niklińska et al. (1999) suggested that global warming would have a greater effect on rates of CO_2 release from soils of old-growth forests. Our laboratory study indicated that 10°C increase in temperature during incubation would cause as much as a 46%–69% increase in soil CO_2 evolution rate in the old-growth Chinese fir forest (Fig. 2).

Predictions of the effects of climate change on soil organic matter decomposition often suggest that higher temperatures will certainly result in increasing decomposition; however, if soil moisture contents are too low or too high, then the effect of temperature will be limited (Ise et al. 2006; Bauer et al. 2008). This is to say that temperature and moisture are important in the controls of decomposition, and the combined effects of these variables need to be considered to understand and predict the response of decomposition in subtropical ecosystems to climate change. Our laboratory incubations were executed at constant moisture and not representative of the conditions in the field; more noteworthy was the fact that moisture would likely not be constant across the different treatments. Thus, further studies are needed to analyze the effects of temperature and moisture on soil respiration.

Despite the importance of soil organic carbon dynamics for predicting future climate change, the soil carbon dynamics of old-growth forests has received little attention at present. It is generally accepted that the soil carbon processes of old-growth forests are changing in response to the changing environment (Zhou et al. 2006). The studied soils were from the typical site in the central growing area of Chinese fir. Also, the 88-year-old Chinese-fir stand is representative in mid-subtropical China with old age and high stand volume (He et al. 2001). Thus, our quantification of the effect of temperature on soil respiration may help us to estimate complex responses and adaptation of belowground processes in old-growth forests to global environmental change. On the other hand, because our observation of the relationship between temperature and soil respiration came from either restricted region or laboratory incubation, the responses of soil respiration to varying temperature need to be verified with applications under field conditions at larger spatial and longer temporal scales.

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